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SHORT COMMUNICATION

MYSIS SALEMAAI IN IRELAND: NEW OCCURRENCES AND EXISTING POPULATION DECLINES

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ABSTRACT

We report three new occurrences of *Mysis salemaai*, a conservationally important glacial relict at the southern limit of its range, in Castlewellan Lake, Lough Scolban and Lough Macnean Upper, in the North of Ireland. This increases the number of lakes in Ireland where the species has been recorded to fourteen. We consider lake area and maximum lake depth as factors that might determine the long-term survival of *M. salemaai* populations and show that these populations tend to occur in relatively large, deep, lakes. We also show that population densities in Lough Neagh and Lough Erne are declining.

INTRODUCTION

The opossum shrimp *Mysis salemaai* Audzijonytë & Väinölä, 2005 (previously known as *M. relicta* Lovén, 1862) is a euryhaline glacial relict, a stenothermic species found in northern Europe, including Ireland, and northern Siberia (Audzijonyte & Väinölä, 2005). The species occurs at its southern distributional limit in Ireland and is the only native member of its taxononmic order in Irish freshwaters, making it conservationally important. It is also an important consumer and prey item for fish in some lake ecosystems (Griffiths, 2007).

Many studies have noted the sensitivity of the *Mysis relicta* species group, of which *M. salemaai* is a member, to high temperatures (see references in Griffiths, 2007), but the effects of oxygen concentration and/or eutrophication are less clear, with some populations tolerating low oxygen concentrations (Horppila *et al.*, 2003; Sandeman & Lasenby, 1980). Penk *et al*. (2014) show that high temperatures and low oxygen concentrations reduce *M. salemaai* survival. Consequently, *M. salemaai* is most likely to have persisted since the last glaciation in cold-water habitats and is therefore most likely to occur in large, deep, cold-water, low productivity, lakes.

Penk (2011) reviewed and updated information on the distribution of *M. salemaai* in Ireland, and provided some information on densities and ecology of the species: Penk *et al*. (2014, Table S3) provide a record, but no density information, for an additional lake, Lough Gowna. The purpose of this short communication is to build on the work by Penk (2011; 2014) by:

(a) documenting three new occurrences of *M. salemaai* in Ireland

(b) investigating the effect of maximum lake depth on *M. salemaai* density

(c) investigating the influence of lake area and maximum depth on *M. salemaai* occurrence

(d) investigating the temporal trends of two large existing populations of *M. salemaai* found in Lough Neagh (Andrew & Woodward, 1993; Griffiths, 2007) and in Lough Erne.

MATERIALS AND METHODS

All *M. salemaai* were caught during daylight by vertical zooplankton net hauls, over varying vertical haul distances. Net types differed between studies in diameter (0.3-0.5m) and mesh size (180-1000μm), but Griffiths (2007) found no effect on estimated densities when comparing the two very different sized nets used in Lough Neagh. All catches, of adults and juveniles combined, are expressed as densities (numbers per m^3).

Penk (2011) provided *M. salemaai* vertical net haul density estimates for most of the lakes in this study. However, *M. salemaai* was found in Oughter Lough only in epibenthic sled samples owing to the shallow nature of this lake. In our analysis the mean density of *M. salemaai* for Oughter Lough was arbitrarily set to the same density value (0.05 individuals.m^{-3}) as in the lake with the lowest density sampled by vertical hauls (Lough Scolban).

We sampled 51 lakes between 2012 and 2013 in the northern part of the island of Ireland. These lakes were sampled seasonally (once in spring, summer and autumn) for chemical and biological properties.

Area and depth data for 136 lakes in Ireland, compiled by Duck and Cawardine (2005), were used to supplement the information in Penk (2011).

LOUGHS NEAGH AND ERNE: TEMPORAL TRENDS IN *M. SALEMAAI* DENSITY

In Lough Neagh *M. salemaai* densities were determined from samples enumerated approximately monthly between 2005-2012 and weekly samples collected between 1993-2005 (Griffiths, 2007). Lough Neagh *M. salemaai* were sampled at two 10m sites, 3km apart, in the north of the lough from 1993-2005 and 2005-2012 respectively. The timing and frequency of sampling in Lough Erne was more variable (4-20 samples per year).

Penk (2011) collected *M. salemaai* samples in March 2009. Mysid catches vary seasonally and, when comparing our data with the Penk dataset, we calculated mean densities for Loughs Neagh and Erne from catches averaged over the February-April, 2005-12 period, due to the low numbers caught.

The long-term trends in Lough Neagh and Erne catch data presented here are calculated as the mean density in all samples collected in each calendar year.

STATISTICAL ANALYSIS

Relationships between *M. salemaai* densities and sampling or lake depth and area were examined by linear regression or product-moment correlation coefficients (*r*). Differences between lakes with or without *M. salemaai* were investigated by univariate analysis of variance, while the effect of sampling site on *Mysis* density in Lough Neagh was tested by analysis of covariance (*F*). All analyses used Systat 13 software.

Loughs Neagh and Erne densities (log-transformed) were examined for temporal congruence by time series analysis. Following standard procedures (Wilkinson, Blank & Gruber, 1996), long term trends in density in each lake series were removed by differencing and then checked that no auto-correlation remained before testing for cross correlation between the two time series. There was one missing and two zero density values for the Lough Erne dataset and densities for these years were automatically estimated by interpolation using local quadratic smoothing.

Lough Erne had a much lower *M. salemaai* density than expected for the vertical haul distance of 55m: it was highlighted as a statistical outlier (Cook's D = 1.03) and omitted from the *M. salemaai* regression analyses.

For cross lake comparisons, *M. salemaai* density estimates (Table 1) were adjusted to a standard vertical haul distance (25m, the mean across samples).

RESULTS

NEW OCCURRENCES: CASTLEWELLAN LAKE, LOUGH SCOLBAN AND LOUGH MACNEAN UPPER

M. salemaai were recorded in just two of the 51 lakes sampled: Castlewellan Lake and Lough Scolban. *M. salemaai* were also found in the gut contents of perch (*Perca fluviatilis* L. 1758) from Lough Scolban (K. Gallagher, unpublished observations). *M. salemaai* was found in Lough Macnean Upper in 1989 (A. G. Fitzsimons, personal communication). This lake was not sampled in the 2012/13 51 lake survey. With the exception of Castlewellan Lake, all previous records come from four large catchments (Shannon, Corrib, Erne and Neagh) (Table 1). Lough Scolban drains to Lough Erne via a short channel. At present, Castlewellan Lake does not appear to have an outflow (R. McFaul, personal communication), but is closest to the Carrigs River which drains to the Irish Sea at Dundrum Inner Bay.

Six *M. salemaai* were also found in August 2005 in sweep net samples from Lough Beg (D. Griffiths, unpublished observations), 2km downstream of Lough Neagh: this probably resulted from washout from Lough Neagh and consequently it is not counted as a new population.

FACTORS INFLUENCING *M. SALEMAAI* DENSITY AND OCCURRENCE

M. salemaai net catch density increased with vertical haul distance (r = 0.55, n = 20, P=0.01; Fig. 1a). Densities increased with maximum lake depth (r = 0.65, n = 11, P<0.05; Fig. 1b). Neither lake area nor trophic state were significant predictors of *M. salemaai* density (r = 0.36, n = 12, P>0.2; r = 0.26, n = 12, P>0.7 respectively).

Lakes with *M. salemaai* had significantly greater areas and maximum depths than those without (Fig. 2), but mean depths did not differ (univariate ANOVAs of log-transformed values $F_{1,129}$ = 64.34, P<0.001, $F_{1,127}$ = 12.82, P<0.001, $F_{1,127}$ = 0.12, P>0.7 respectively).

LOUGH NEAGH AND LOUGH ERNE: TEMPORAL TRENDS IN *M. SALEMAAI* DENSITY

There was no significant difference in *M. salemaai* temporal trends between the two Lough Neagh sites (ANCOVA; slopes $F_{1,17}$ = 0.23; intercepts $F_{1,18}$ = 0.00), so we present the analysis for the combined data after dropping one of the data points, selected at random, for the overlap year of 2005. While mean densities have fluctuated over time there were significant declines in both lakes (Lough Neagh r = -0.74, n = 20, P<0.001; Lough Erne r = -0.39, n = 24, P<0.05). The density of *M. salemaai* in Lough Neagh declined by 96% in mean abundance between 1993 and 2012, while in Lough Erne there was a much weaker decline of 58% over the same period (Fig. 3). Over this period there was no significant cross correlation between the two time series, contrary to what would be expected from a large-scale environmental effect on population density.

DISCUSSION

Mysis salemaai is a euryhaline, relatively young, species which is thought to have colonised freshwaters from coastal populations towards the end of the last glaciation (Audzijonyte & Väinölä, 2006). In Ireland, *M. salemaai* populations have been found in both large and small lakes (Penk 2011; 2014 and this paper). Long-term population persistence is most likely in large, deep, lakes as these waterbodies can potentially support larger populations: our results are consistent with this statement. Population density was greater in deeper lakes. These lakes are likely to stay cooler than shallow lakes in summer because of their greater volume.

M. salemaai populations in Lough Scolban and other small lakes might also be maintained in the long-term because of connections to large lakes within the catchment, which may permit recolonization in the event of local extinction (the rescue effect, Brown & Kodric-Brown, 1977). Recolonization would be more likely to occur between lakes at similar elevations, connected by short channels with low discharges: Lough Scolban is only 4m higher than Lough Erne and connected by a channel about 2km long, while Lough Macnean Upper, although approximately 20km from Lough Erne, is only 2m higher. Penk & Minchin (2014) showed that *M. salemaai* moved into shallow waters in autumn, a behaviour conducive to colonisation of lakes via rivers.

However, Castlewellan Lake is a small lake not currently connected to any of the other catchments with *M. salemaai* populations and all but the Castlewellan Lake population were found in catchments which drain to the west or north of Ireland. There is geological evidence of drainage from Lough Neagh to the southeast during the last glacial period (Knight, 2002) and, while there is no evidence of a connection, it is possible that water flowed into Castlewellan Lake postglacially (S. Roberson, personal communication). Colonisation from the sea seems unlikely given the lake's elevation (twice that of other populations) and proximity to the coast, implying a steep channel gradient if a connection existed in the past. Hull (1881, p12) notes, without further comment, that 'Castlewellan Lake is only partly artificial': a smaller lake appears to have been extended by previous estate owners (R. Kernohan, personal communication).

In the latter half of the 20th century, intentional introductions of *Mysis relicta* and *M. diluviana* Audzijonytë & Väinölä, 2005 were common in Scandinavia and North America respectively, in an effort to boost salmonid fisheries (Nesler & Bergersen, 1991). Castlewellan Lake is stocked with brown (*Salmo trutta* L.) and rainbow trout (*Oncorhynchus mykiss* Walbaum)(body weight about 400g) annually, between January and October, from Movanagher Fish Farm, about 20km downstream of Lough Neagh. A Ministry of Agriculture for Northern Ireland (1969) report notes large numbers of *Mysis relicta* (now *M. salemaai*) in the fish farm water supply and outlines the intention to introduce them to Castlewellan Lake, as a natural source of fish food 'to a lake where it is known they are not indigenous'. Following introduction in March 1969, surveys conducted in Castlewellan Lake in November 1979 and 1980 revealed the presence of *Mysis* in the stomachs of 50% and 21% respectively of fish (presumably trout) caught. Prior to this, stomach content analysis had not shown *Mysis* to be present in the lake (Department of Agriculture Science Service, 1980). While the information in the reports lacks detail it does suggest that the *M. salemaai* population in Castlewellan Lake is most likely to have been introduced. It's persistence to the present day illustrates the potential for establishing a successful, non-indigenous, population.

Are there still more *M. salemaai* populations yet to be discovered in Ireland? The species has not been recorded from Lough Mask, a large deep lake, separated from Lough Corrib, where it does occur, by a short, low gradient, channel: this might be a real absence or simply due to inadequate sampling. The sampling protocol for zooplankton in Ireland tends to favour the use of vertical net hauls in preference to horizontal tows. The majority of Irish lakes are shallow and consequently *M. salemaai*, an active swimmer, is more likely to move away during net placement and hence less likely to be sampled by the short vertical hauls taken in shallow lakes. However, small, shallow, lakes are also less likely to persist over geological time than larger, deeper ones (Wetzel, 2001) and so, unless closely connected to large lakes, *M. salemaai* populations are unlikely to be found in shallow lakes.

The catch density-depth analysis identified Lough Erne as a statistical outlier, with only about 10% of the *M. salemaai* density expected for a lake of this depth. It is not clear why this lake has a low *Mysis* density: it is not extreme in terms area or productivity although it is deeper than the other *Mysis* lakes. Zebra mussel, *Dreissena polymorpha* (Pallas, 1771), arrived in Lough Erne in 1996. The species has impacted the Erne ecosystem, by, for example, reducing plankton abundance (Maguire & Gibson, 2005), with potential impacts on *M. salemaai* densities. However, if zebra mussels had significantly impacted *M. salemaai* a marked difference would be expected in pre- and post-invasion densities: no such shift is apparent in Fig. 3.

Two of the largest lakes in Ireland, Loughs Neagh and Erne, show *M. salemaai* population declines. In Lough Neagh densities have dropped from around 300 m^{-3} in 1993, much higher than recorded in other Irish lakes (Table 1), to a more typical density of about 1 m^{-3} in 2012. *Mysis* declines potentially affect on other components of the ecosystem. In particular, *M. salemaai* is an major food source for cold water fish in Lough Neagh (Bigsby, 2000; Kirkwood, 1996; Vaughan, 2009), including the conservationally important glacial relict *Coregonus autumnalis* (Pallas, 1811). Griffiths (2007) concluded that changing temperatures and, to a lesser extent, eutrophication were the factors driving population declines in Lough Neagh between 1994-2005. The absence of a correlation between annual fluctuations in density in the two lakes suggests that other factors in addition to temperature could be involved. The recent discovery of the bloody-red shrimp (*Hemimysis anomala* G. O. Sars, 1907) in Lough Erne (Gallagher *et al.*, 2014) may also reduce *M. salemaai* densities in the future by competition, as *Hemimysis anomala* has a higher feeding rate than *M. salemaai* (Dick *et al.*, 2013).

If rising temperatures are driving the decline in the Irish *M. salemaai* populations then their long-term survival is in doubt, given the expected warming in Ireland (most models predict rises of 3-4°C) this century (Dunne *et al.*, 2008; Sweeney & Fealy, 2002; Woodward, Quaife & Lomas, 2010). Translocations to cold-water lakes, i.e. to higher elevation water bodies, is a possibility to maintain the species. However, many previous introductions of *M. salemaai* have had deleterious effects on other components of the ecosystem (Nesler & Bergersen, 1991), so this conservation option needs careful consideration.

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Table 1—Summary features of Irish lakes and estimated spring densities of *Mysis salemaai* populations.

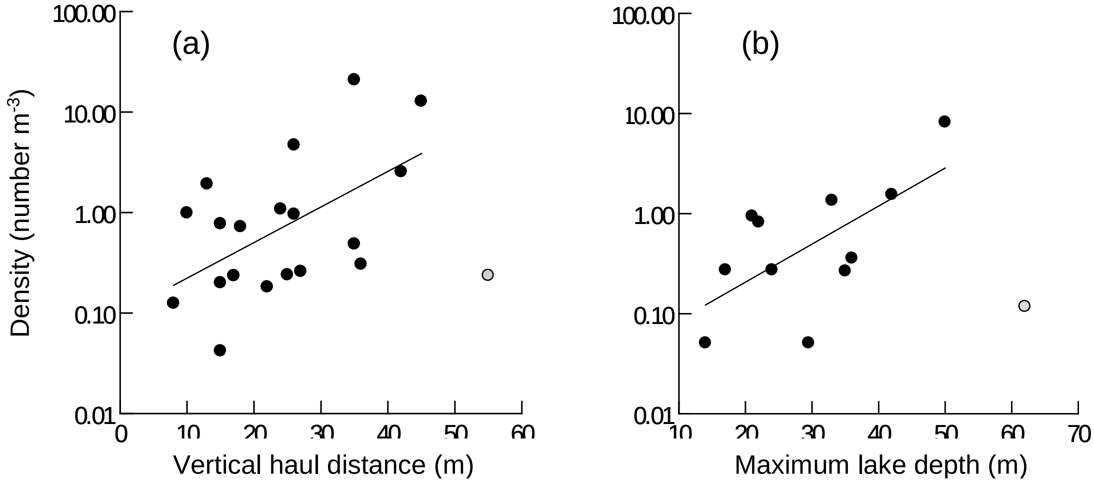
Lake	Area (km^2)	Mean depth (m)	Maximum depth (m)	Altitude (masl)	Catchment	Trophic state	*M. salemaai* density ($number.m^{-3}$)	Data source
Allen	33.3	4.5	42	42	Shannon	Oligotrophic	1.55	Penk (2011)
Castlewellan	0.36	6.2	21	120	Carrigs?	Eutrophic	0.94	This study
Corrib	166	12	50	2	Corrib	Oligotrophic	8.20	Penk (2011)
Derg	128	7.6	36	34	Shannon	Mesotrophic	0.36	Penk (2011)
Derravaragh	10.8		24	64	Shannon	Oligotrophic	0.27	Penk (2011)
Erne	110	11.9	62	46	Erne	Mesotrophic	0.12	This study
Garadice	3.8	4.7	17	54	Erne	Oligotrophic	0.27	Penk (2011)
Gowna	11.2	3.8	20	62	Erne	Eutrophic		Penk *et al.* (2014)
Key	8.7	5.1	22	38	Shannon	Mesotrophic	0.82	Penk (2011)
Macnean Upper	9.5	4.4	23	48	Erne			Fitzsimons (pers. comm.)
Neagh	385	8.9	33	12	Neagh	Eutrophic	1.36	This study
Oughter	11.1	2.2	14	50	Erne	Eutrophic	0.05	Penk (2011)
Ree	99.8	6.2	35	38	Shannon	Mesotrophic	0.27	Penk (2011)
Scolban	0.58	7.8	30	50	Erne	Oligotrophic	0.05	This study

Figure legends

Fig. 1 (a) *Mysis salemaai* densities for different vertical haul distances in different lakes. (b) Mean *M. salemaai* density as a function of maximum lake depth, after adjusting to a standardised vertical haul distance. Lough Erne (light fill point) was omitted from the regressions.

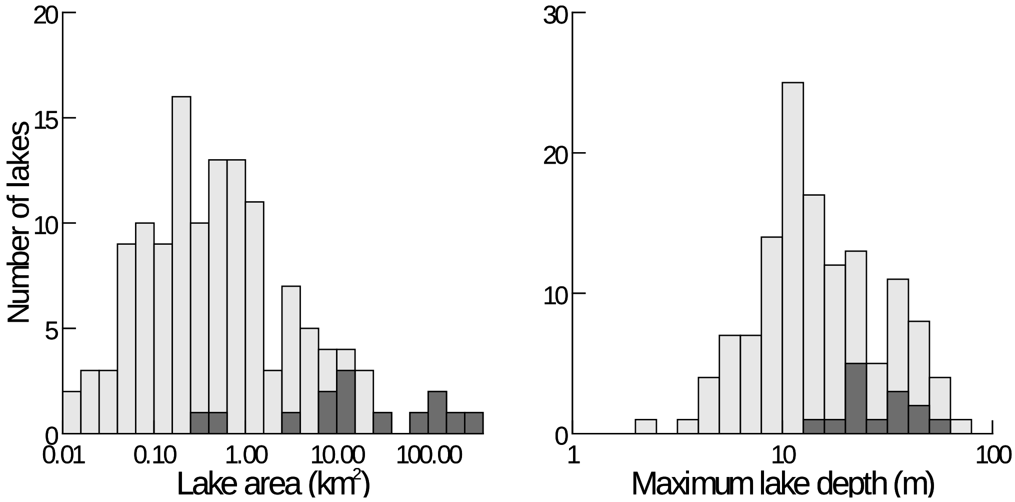
Fig. 2–Histograms of lake area and maximum depth for lakes with (dark shading) and without (light shading) *Mysis salemaai* populations.

Fig. 3–Temporal trends in mean *Mysis salemaai* density in (a) Lough Neagh and (b) Lough Erne.



100.00
10.00
1.00
0.10
0.01
(a)
Density (number m-3)
0
10
20
30
40
50
60
Vertical haul distance (m)
(b)
10
20
30
40
50
60
70
Maximum lake depth (m)

Fig. 1


Number of lakes
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10
5
0
0.01
0.10
1.00
10.00
100.00
Lake area (km2)
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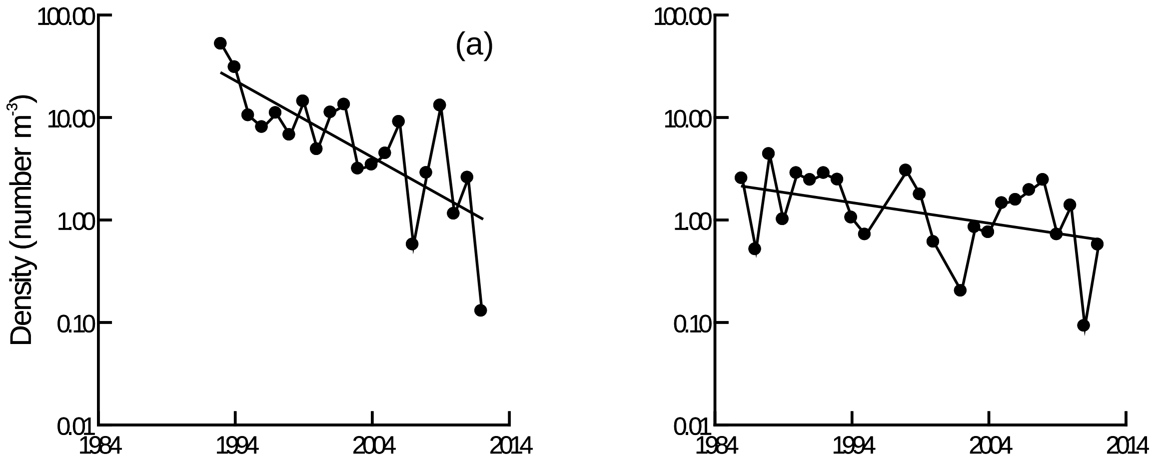
20
10
0
1
10
100
Maximum lake depth (m)

Fig. 2


100.00
10.00
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1984
1994
2004
2014
Density (number m-3)
(a)
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10.00
1.00
0.10
0.01
1984
1994
2004
2014

Fig. 3